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Navy Altimeter Data Requirements

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Navy requirements for altimeter data are driven mainly by the operational systems for mesoscale ocean circulation monitoring and acoustic prediction. Specification of requirements also considers development toward future systems that will provide tidal height and currents, regional circulation in semienclosed basins, and wave heights. We provide a short synopsis of present systems for describing the ocean environment based on altimeter data. Typical mesoscale time and length scales, determined from historical altimeter data, guide the specification of time and space resolution requirements for future altimeter systems. Accuracy requirements are based on the propagation of sea surface height errors into environmental estimates of the three-dimensional temperature and salinity fields and effects on sonar performance.

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CONTENTS

EXECUTIVE SUMMARY

This document examines the effects of altimeter data resolution and errors on Navy products from the Navy Modular Ocean Data Assimilation System (MODAS) and numerical model assimilation. Based on these results, we provide the following recommendations for future operational altimeter requirements.

- Sea surface height, atmospheric correction parameters, and orbit solutions are required within 48 hours. Wave heights are required within 3 hours.
- The required instrument white noise level must be below 3 cm rms.
- The required total range error must be under 5 cm (peak error) after all atmospheric corrections are applied.
- Required real time orbit solutions must contain under 1 m error at 1 cycle per satellite orbit revolution (cpr) and less than 2 cm integrated errors at higher frequencies.
- An exact repeat orbit must be required, and the satellite must be held to within a 1 km wide swath of a predefined ground track.
- The required repeat period must not be less than 20 days.
- A minimum of one instrument is required. With only one instrument, this data must be used in conjunction with systems such as MODAS and NRL Layered Ocean Model (NLOM).
- Two altimeter instruments are recommended on the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) for error reduction and redundancy.
- Major tidal constituents should not be aliased to frequencies that contain significant ocean variability. These frequencies include the annual, semiannual, and mean.

NAVY ALTIMETER DATA REQUIREMENTS

1. INTRODUCTION

This document provides recommendations on the Navy requirements for satellite altimeter data. The oceanographic features that significantly affect acoustic propagation determine the altimeter measurement accuracy, sampling distribution, and subsequent requirements. Present operational systems ingesting altimeter data in real time are described, and developmental work for future operational systems is also presented. Our purpose is to provide a reference document for planning future satellite missions. It is not possible for a single satellite altimeter to fulfill all operational requirements. As is demonstrated in this document, a single satellite is not capable of providing measurements of all desired time and length scales. Almost every satellite mission is a compromise between competing measurement requirements and available resources. Single satellite ground tracks may be optimized to provide measurement for a majority of processes of interest. For optimizing a sampling strategy, requisite information includes the dominant length and time scales of typical ocean features throughout the world. Thus, in addition to providing Navy requirements, we provide an estimate of the signal to be measured.

Present Navy operational systems are driven primarily by the need to monitor ocean mesoscale variability. However, this is not the only application for which the Navy requires altimeter data. The estimation of tides on continental shelf and coastal areas is an important problem. Altimeter data offers the capability of more accurate tide prediction globally and on the continental shelf than is possible using only coastal tide stations. The application of altimeter data for measurement of flow through critical straits, such as the Tsushima Strait inflow to the Japan/East Sea, is also viewed as an important constraint on local numerical models. Thus, while present operational systems focus mainly on mesoscale variability, development of future systems will apply altimeter data to a much broader scope.

2. NAVY ALTIMETER DATA APPLICATIONS

The Navy requires altimeter data for operational oceanographic applications and scientific research. The ocean environment plays a critical role during Navy operations. Continuous real-time monitoring of the ocean environment is the only manner to accurately obtain many of the required environmental parameters.

Naval Ocean Environmental Parameters and Applications for which Altimeter Data Are Used

- **Acoustic environment** that affects ocean temperature, salinity, and density, which in turn impacts antisubmarine warfare (ASW)
- **Currents** for mine drift, optimal track ship routing, and search and rescue operations

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- **Tidal currents** that affect suspended sediment loads and optical properties, which in turn control mine detection
- **Wave height** measurement for optimal track ship routing and coastal operations

Ocean Phenomena that Affect Environmental Parameters

- **Mesoscale eddy circulation.** Mesoscale variability (e.g., ocean eddies, meandering fronts, and currents) has a significant impact on the three dimensional (3-D) temperature and salinity structure. The generation of rings, eddies, and frontal meanders is not predictable even when accurate forcing estimates are available. Thus, continuous monitoring of the ocean mesoscale is necessary. The altimeter provides the required capability to observe the eddy field even in cloud conditions. The altimeter observations are used in combination with statistical and numerical models to depict the 3-D temperature and salinity variations due to the eddy field. An accurate numerical model assimilating altimeter observations can depict and forecast the evolution and movement of observed features with skill on time scales of one month or more.

  Figure 1 shows one example of the effect of the mesoscale circulation on the ocean environment for the Japan/East Sea. The acoustic signal excess provides an estimate of the acoustic signal of an object relative to the background noise level. If the acoustic signal excess is greater than zero, then the reflected acoustic signal of an object is greater than the background noise, and the object is detected. Initially using a climatological density field based on the Generalized Digital Environmental Model (GDEM) (Teague et al., 1990), the acoustic signal excess indicates a wide field of view. During this time, an intense airborne expendable bathythermograph (AXBT) survey provided the true synoptic environment. The true acoustic signal excess is significantly different from the climatologically derived field, revealing a blind spot to the northeast of the acoustic receiver and extended ranges to the northwest. This information is crucial in the planning of how ASW assets are deployed. The purpose of altimeter data is to provide a replacement for the intensive large-scale AXBT survey.

- **Large-scale circulation.** The local environment is a product not only of the local forcing; it can also be strongly controlled by remote and large-scale circulation variations. Wind stress, heat fluxes, and buoyancy fluxes across the ocean basins drive the gyre-scale circulation. The basin-scale ocean circulation intensifies along the western boundary of the ocean basins, and the western boundary currents have a strong impact on energy available to the nondeterministic mesoscale eddy field. El Niño events impact remote environment by generating Kelvin and Rossby waves. Changes in the circulation of basin-scale gyres also change the energy available to the eddy field. Accurate measurement of the large-scale circulation aids in correcting for inaccurate wind stress and other forcing functions in numerical model assimilation.

- **Steric anomaly.** The thermal expansion of the upper ocean caused by heat flux changes the density structure in the upper ocean. The combination of altimeter-observed sea surface height variations with sea surface temperature provides an estimate of the total heat content in the upper ocean and can be used to estimate vertical profiles of temperature and salinity.

- **Tides.** Ocean tides represent the first order process in many continental shelf and coastal regions. Tidal currents and heights can have a large impact on swimmer and landing operations at the coast. In addition, tidal currents play a large role in generating the turbulent bottom boundary layer that resuspends sediments into the water column, influencing optical properties.

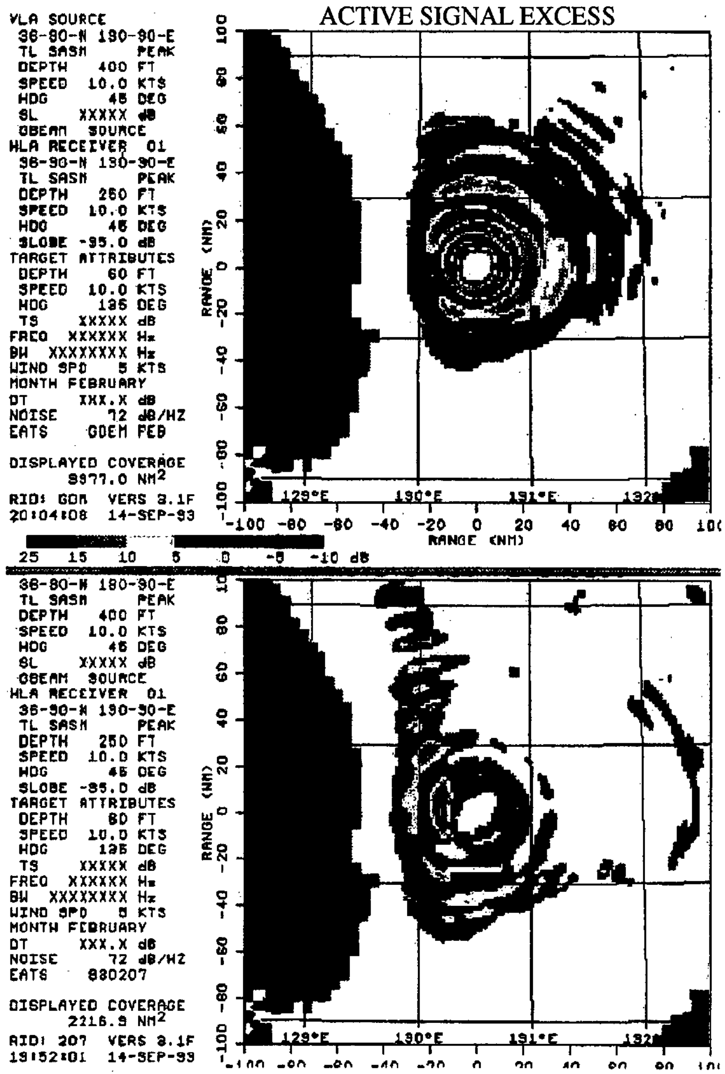

Fig. 1 —The acoustic signal excess calculated from (top) a climatological density field based on GDEM and (bottom) an AXBT survey in the Sea of Japan off the east coast of South Korea. The results from the AXBT survey indicate a much smaller area of detectability than the results from the GDEM survey.

- **Wave heights.** Wave heights affect ship routing in the open ocean. In the coastal environment, knowledge of wave heights is critical for the planning and execution of landing craft operations.

3. OPERATIONAL NAVY SYSTEMS REQUIRING ALTIMETER DATA

At present there are two systems under operational test within the Navy that require altimeter data. Operational test is the last step in the transition process from a research product to an operational Navy product. The systems provide complementary capability and are designed to work with one another. These systems include statistical modeling based on regression of climatological data and numerical ocean modeling based on fundamental dynamical equations. Together the two paths represent a comprehensive effort to provide the most accurate environmental estimates possible. The design of these systems focuses on the ability to estimate environmental variations associated with the open ocean mesoscale circulation.

MODAS

The Navy Modular Ocean Data Assimilation System (MODAS) uses historical in situ data to derive statistical relations between surface observations (dynamic height and temperature) and subsurface quantities (temperature and salinity). Given a measure of the surface height and surface temperature, it is possible to reconstruct the subsurface temperature and salinity profile based on the derived surface to subsurface relations (Carnes et al., 1990, 1994). The statistical correlations vary spatially and seasonally since the vertical relations depend on the local environment and dominant oceanographic processes.

The MODAS system presently uses real-time altimeter data from TOPEX/POSEIDON and ERS-2 to produce global sea surface dynamic height on a 1/8° grid. Sea surface temperature is also generated on a 1/8° grid based on real-time advanced very high resolution radiometer (AVHRR) data. The gridding of both the surface height and temperature is carried out to retain the local mesoscale variability and not to simply produce the large-scale global dynamic height. The operations are performed globally to allow access to every region across the world. Using the gridded surface height and temperature, MODAS uses the statistical relations of surface to subsurface properties to generate the subsurface temperature and salinity profiles. The altimeter processing and MODAS analyses are run daily, and results are made available at www7300.nrlssc.navy.mil/altimetry. Operational runs that incorporate in-situ profile data are on the classified network at www.navo.navy.mil

Numerical Models

Altimeter data assimilation impresses the nondeterministic mesoscale field into numerical models. The NRL Layered Ocean Model (NLOM) (Wallcraft and Moore, 1997) is presently running at the Fleet Numerical Meteorology Oceanography Center (FNMOC) in Monterey, California, and is assimilating altimeter data daily. The eddy characteristics (length scales and propagation speeds) in the numerical models have been evaluated relative to prior altimeter data with good agreement (Jacobs et al., 1996). The NLOM version at FNMOC under operational test is a 1/4° resolution global primitive equation model with six layers (Metzger et al., 1998). Planned upgrades by 2001 are the transition of a 1/8° global system with embedded 1/16° Pacific (north of 20°S) and 1/32° subtropical Atlantic (9°-51°N), including the Caribbean and Gulf of Mexico. In addition to the NLOM, operational Princeton Ocean Model (POM) systems are also implemented at NRL and FNMOC. The NLOM system uses the altimeter sea surface height (SSH) and sets subsurface structure using statistics based on the NLOM model, whereas POM uses MODAS statistics to set subsurface structure.

The relocatable POM systems use the 3-D temperature and salinity output of MODAS as initial conditions for ocean environment prediction. MODAS uses the sea surface height (SSH) output from NLOM to generate 3-D temperature and salinity fields in a prediction mode.

4. REQUIREMENTS JUSTIFICATION

The ocean feature time and space scales dictate the requirements for altimeter data timeliness, spatial and temporal sampling, and accuracy. Because the present operational systems focus mainly on the mesoscale variability within the ocean, the justification presented here is in terms of observing the mesoscale ocean circulation. In Section 5, we discuss systems that are presently under development and are expected to transition to operational use in the coming years. Thus, we also take into account requirements for these systems.

Ocean Spatial and Temporal Characteristics

The two dominant characteristics of the mesoscale ocean circulation are its nondeterministic and small-scale nature. Mesoscale fronts and eddies are generated by instability processes within the ocean. These instabilities are turbulent in nature and derive their energy from the vertical (baroclinic) or horizontal (barotropic) velocity shear. Because of their nonlinear formation and chaotic nature, the generation of mesoscale features cannot be accurately depicted in atmospherically forced ocean models without oceanic data assimilation. Though forcing external to the ocean may sometimes play a roll in aiding the generation of mesoscale events, the frontal meandering and eddy shedding events of the world oceans remain largely nondeterministic.

Given an ocean model with accurate forcing and an accurate initial state, the model mesoscale field diverges from reality on a time scale of the order of the mesoscale time scale (approximately 30 days). To provide on-demand analyses of the ocean environment, it is necessary to continuously observe the ocean mesoscale field. Observed mesoscale features may be impressed into an ocean model through a range of numerical assimilation techniques (Fig. 2). Once the model properly represents the synoptic mesoscale field by assimilating altimeter data, this model may provide skillful forecasts on time scales of a month or more.

The ocean mesoscale prediction problem is similar to atmospheric weather prediction, though the mesoscale circulation spatial scales are much shorter within the ocean than the atmospheric high and low pressure systems. While it is possible for an atmospheric model to predict the movement of weather systems and associated fronts, the prediction of weather system formation far in advance (more than 10 days) is not possible.

The spatial scale of the mesoscale circulation varies substantially over the globe. Typical length scales range from a few hundred kilometers near the equator to 50 km at midlatitudes. SSH amplitudes of mesoscale features range from 5 to 50 cm, which is comparable to amplitudes of the large-scale ocean circulation. Because of the short length scales involved, the mesoscale field can generate significant spatial height, temperature, and salinity gradients. The mesoscale environmental gradients are typically much larger than the environmental gradients due to the large-scale circulation or mean ocean state (Fig. 3).

Because the mesoscale circulation derives its energy from the shear within the ocean (Pedlosky, 1987) and because the shear is mainly associated with the large-scale circulation of the ocean gyres and the associated narrow boundary currents, there is a strong connection between the large-scale ocean circulation and the mesoscale field. Although the large-scale circulation (> 500 km) is mainly wind driven and deterministic, its circulation measurements are useful to improve model accuracy by offsetting errors in the wind fields. By improving ocean model large-scale circulation, we ensure the accurate positioning of the energy that feeds the mesoscale circulation.

The large-scale ocean circulation also exerts a significant influence on the local ocean environment of many regions in the world. For example, El Niño events within the equatorial Pacific generate perturbations along the west coasts of the American continents; typically, sea levels rise soon after an El Niño event. The increased northward transport along the North American continent provides a ready energy source to generate mesoscale turbulence. Large intense eddies are typically observed in the eastern Pacific off the American coasts following an El Niño event. The strength of the major western boundary currents, which is determined by the large-scale subtropical gyre circulation, also has a large influence on the generation of mesoscale energy. Thus, improving accuracy of the basin scale circulation will improve model accuracy for

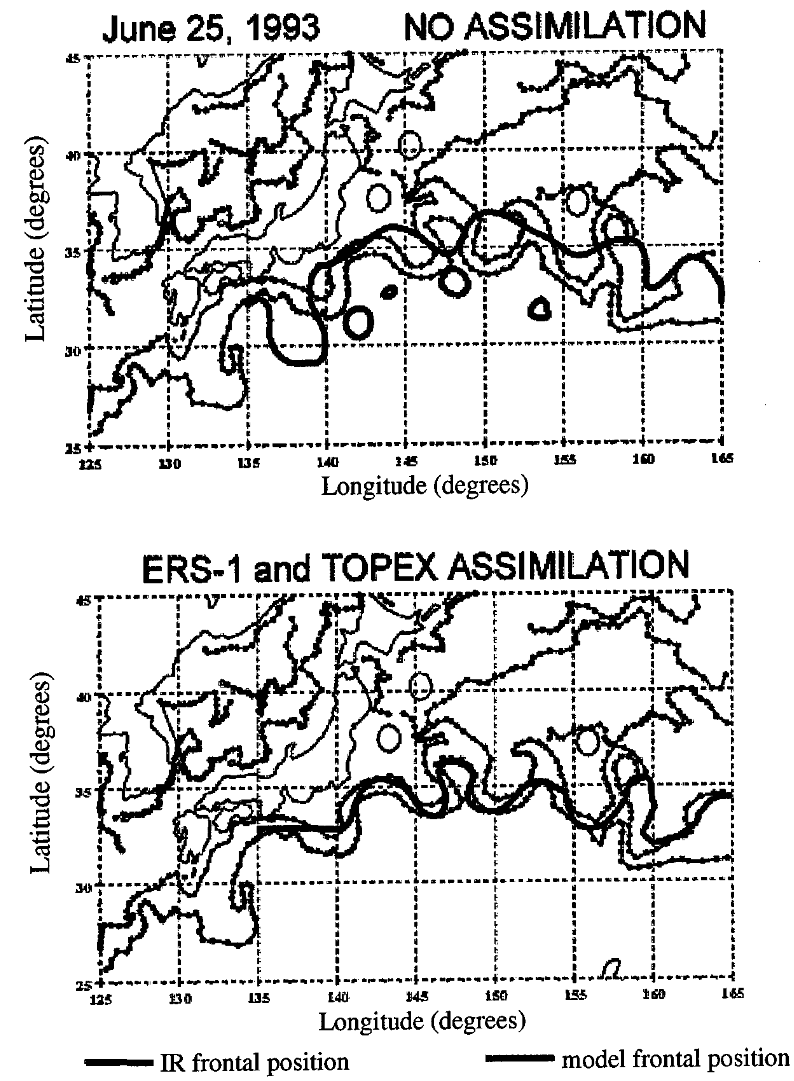

Fig. 2 — An accurate numerical model may generate realistic mesoscale variability in terms of eddy scales and propagation speeds. However, the observed mesoscale events are chaotic, and the numerical model does not generate the same events observed by satellite. Comparison of the Kuroshio Extension path observed from thermal imagery (red lines) to that in a numerical ocean model forced by synoptic wind stress (blue lines) indicates a poor agreement between the observed and modeled path (top). By assimilating altimeter data, the observed mesoscale field is impressed into the model, and the model generates the observed Kuroshio Extension path (bottom). Continued integration of the model may maintain the field and produce skillful forecasts (Smedstad et al., 1997).

predicting the propagation and dissipation of the mesoscale field. Measurements required to describe large-scale ocean circulation are obtainable with a satellite altimeter mission designed to monitor mesoscale circulation. Therefore, we do not focus attention toward the large-scale circulation problem within this document.

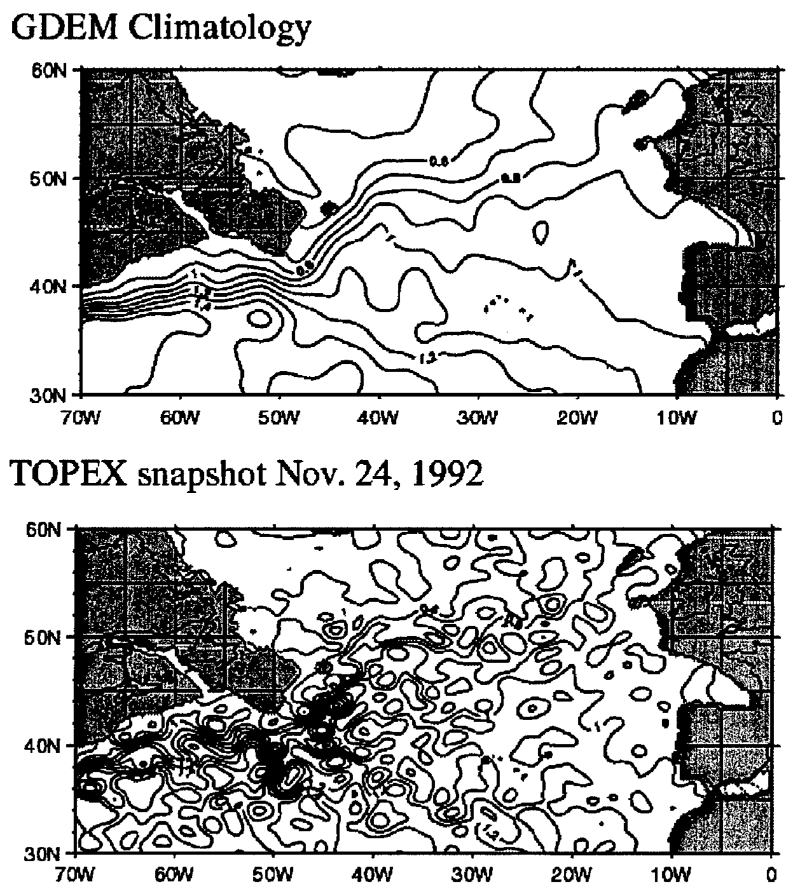

Fig. 3 — A comparison of the climatological dynamic height (top) from the Generalized Digital Environmental Model (GDEM) (Teague et al., 1990) and a snapshot from the MODAS system using TOPEX altimeter data. The short spatial scale of the mesoscale variability creates gradients that are larger than the gradients of climatology.

Mesoscale Characteristics

We derive the mesoscale field characteristics from a combination of TOPEX/POSEIDON, ERS-1/2, and Geosat-ERM altimeter data. These data sets cover a 10-year time period, and a significant overlap occurs between the TOPEX/POSEIDON and ERS-1/2 data sets. The observed autocovariance function provides the required mesoscale statistics. The simultaneity of TOPEX/POSEIDON and ERS-1/2 satellite data provides additional statistical information that is not available from each satellite individually. Prior to generating the mesoscale statistical information, the large-scale variability (> 750 km) is removed from all the altimeter data sets. The data sets are consistently referenced to the mean sea surface height over the first 6 years of the TOPEX/POSEIDON mission. Corrections are made within MODAS and NLOM to account for decadal cycles that may bias the 6 years of altimeter data relative to the climatological state.

The sampled autocovariance function provides the information necessary to measure the mesoscale characteristics by indicating how the sea surface height at one point relates to data that are offset in time and

space. Because the nature of the eddy mesoscale field varies significantly across the globe, a binned autocovariance function is generated every two degrees latitude and longitude. Figure 4 presents one example of the binned autocovariance function.

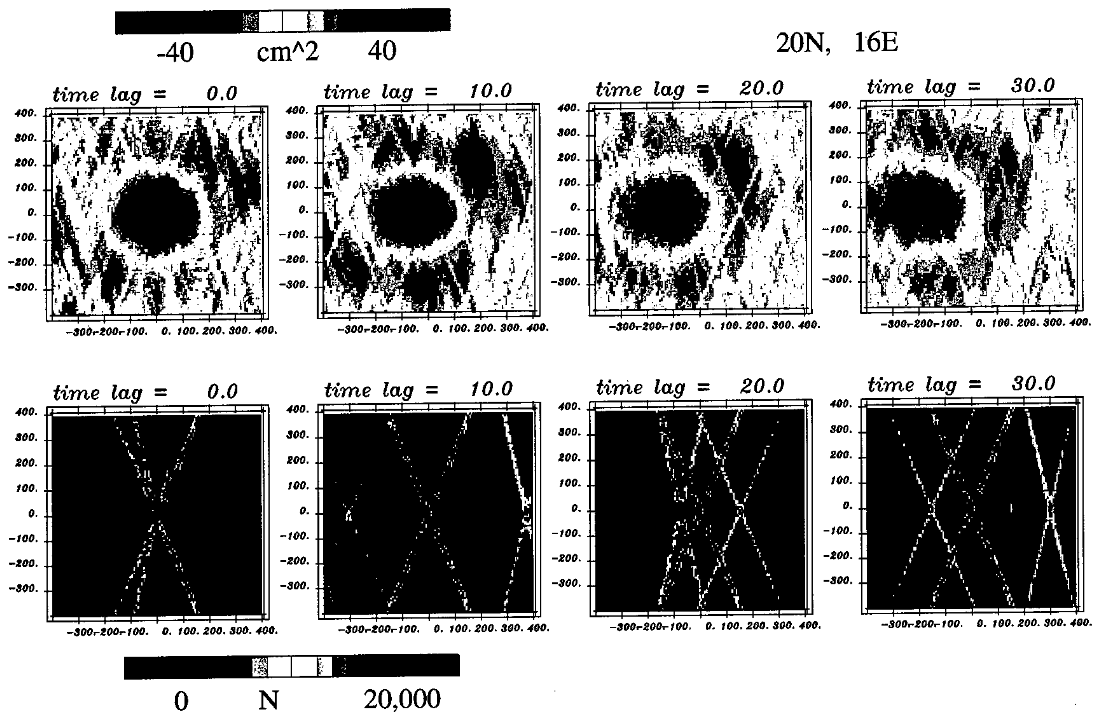

Fig. 4 — The time-space sampled autocovariance function at 20°N 160°E based on the Geosat-ERM, TOPEX/POSEIDON, and ERS-1/2 data sets. The autocovariance (top) is binned in 10 km × 10 km spatial bins and 2.5-day time bins (only a subset of the total function is shown). The autocovariance indicates the dominant length scales, time decorrelation scales, and propagation speed and direction. For example, the autocovariance function here indicates that anomalies generally propagate westward 200 km in 30 days, and the length scale is about 100 km. The number of samples in each 10° × 10° × 2.5-day bin (bottom) is generally above 2,000. The large number of samples and spatial density is mainly due to the simultaneity of the TOPEX/POSEIDON and ERS-1/2 satellites.

A Gaussian functional form is fit to the binned autocovariance function at each two-degree latitude and longitude point. The Gaussian function allows estimation of 2-D length scales, time scale, and propagation speed and direction parameters. Figure 5 presents the resulting time scale, zonal length scale, and zonal propagation speed. The time and length scales are the e-folding distance of the Gaussian function that represents the binned autocovariance function.

Sampling Strategies

For a single altimeter satellite, the product of the repeat cycle period and the distance between ground tracks at the equator are proportional to the orbit period. Thus, there is a trade-off between the spatial sampling capability and temporal resolution. There have been three dominant sampling schemes for single altimeters (Geosat-ERM, TOPEX/POSEIDON, and ERS-1/2). Each satellite is capable of observing synop-

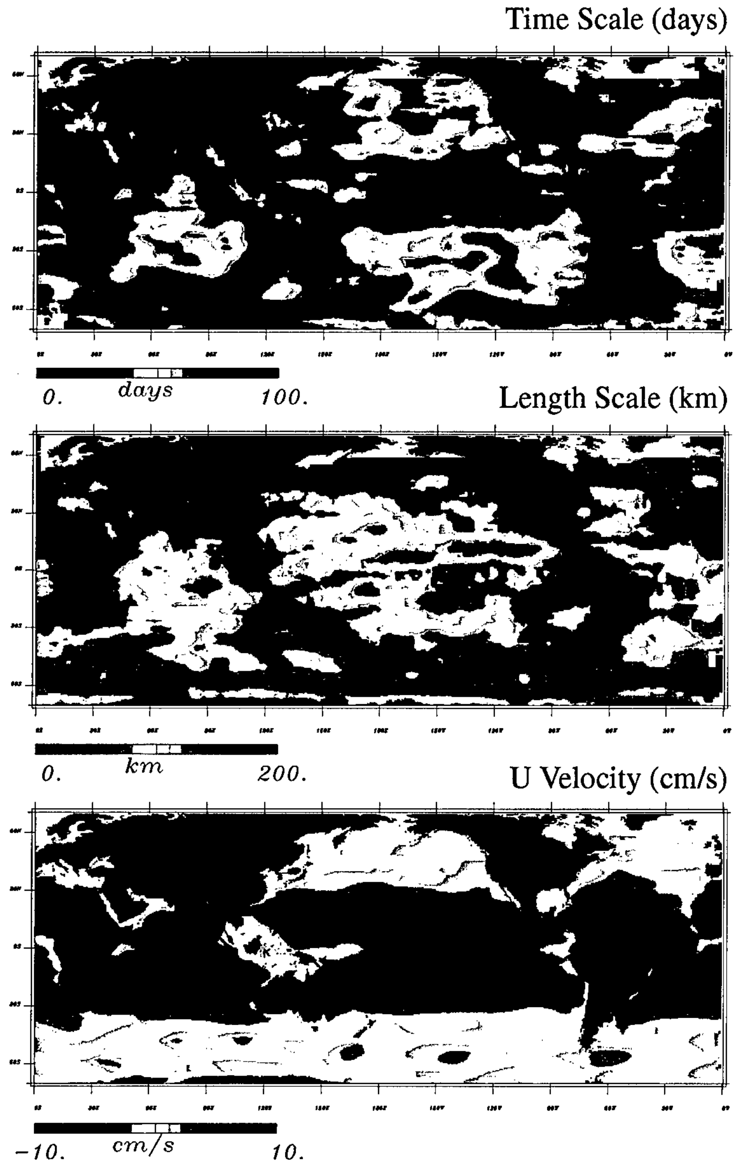

Fig. 5 — Time scales (top), zonal length scale (middle), and zonal propagation speed (bottom) are determined from the observed autocovariance functions on a $2° \times 2°$ grid. These are the mesoscale characteristics that must be resolved by an altimeter sampling system. Comparison of these scales to scales resolvable by various altimeter systems is made in Fig. 6.

tic features that are larger than the ground track separation and time that are scales greater than the repeat cycle time. The temporal and spatial resolution of an altimeter satellite may be viewed as an area covered in the wavelength/time period domain. Wavelengths and time periods to the upper right of the satellite design point in wavelength/time period space are resolvable by a single satellite altimeter. Figure 6 shows the design points of previous altimeter satellites. If the orbit period of all satellites were equal, then all satellite design points would fall on the same line. However since the TOPEX/POSEIDON orbit period is longer than both the Geosat-ERM and ERS-1/2 orbit periods (since TOPEX/POSEIDON is at higher altitude), the TOPEX/POSEIDON design point falls slightly above the Geosat-ERM and ERS-1/2 line.

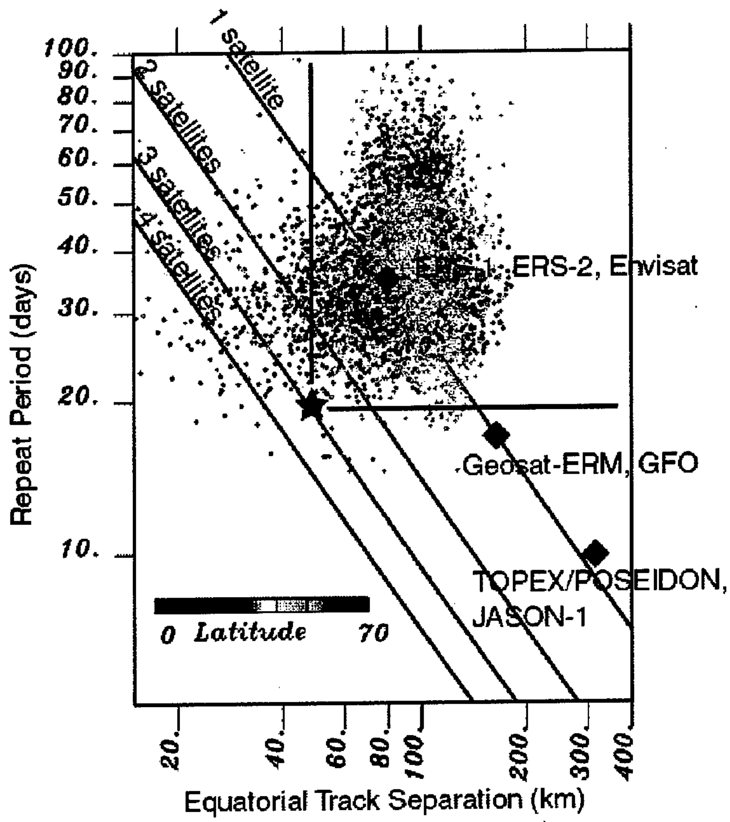

Fig. 6 — The area to the upper right of the system design point measures the spatial and temporal resolution capabilities of a system of coordinated altimeter satellites. Previously flown and presently planned single altimeter system design points are plotted. The colored points indicate the observed mesoscale time and space characteristics (e-folding length scales) with the color shading indicating the latitude. The zonal length scale is divided by the cosine of latitude to account for the latitudinal satellite ground track convergence. A system of three altimeter satellites is capable of measuring a majority of the mesoscale circulation at all latitudes.

At the mission design stage, the design point of a single satellite altimeter may be placed anywhere along the single satellite line. The choice of time and length scales measured may be made to cover the largest portion of the mesoscale field possible. Figure 6 also shows the previously derived mesoscale characteristic time and length scales. The zonal length scale is divided by the cosine of latitude to account for the convergence of the satellite ground tracks with latitude. The design point for the single altimeter should be chosen so that the area to the upper right of the point encompasses the largest possible portion of the mesoscale field characteristics. None of the single altimeter systems are capable of covering a majority of the range of the mesoscale field characteristics.

Two altimeter satellites may be coordinated in any of several simple manners. For example, two satellites may be placed in the same ground track separated so as to reduce the repeat cycle by half. The satellites may also be placed so that the ground tracks interleave, reducing their space separation by half. By coordi-

nating two satellites in this manner, the design point of the two-satellite system falls on a line that is to the left of the line of design points for a single satellite system. The design point of a two-satellite system covers a larger region of the wavelength/time period domain than the single satellite design point. Three coordinated satellites with equatorial track separation of 50 km and a 20-day repeat period are required to measure a large portion of the mesoscale circulation (Fig. 6). A less efficient system may be composed of two satellites with a 60-km equatorial separation and 25-day repeat. A single nadir-observing satellite is not capable of synoptically observing a majority of the mesoscale field.

Measurement Accuracy

Measurement accuracy is determined from the MODAS system by calculating the propagation of sea surface height error into temperature and salinity errors. Sea surface height errors in excess of 5 cm generate temperature and salinity errors that are of unacceptable magnitude (Figs. 7 and 8). Thus, the operational requirement is for measurement errors to be less than 5-cm peak amplitude on the length scales equal to or greater than the length scales of mesoscale variability. Orbit solution error is one exception to this and is discussed further below.

Contributors to errors:

- Instrument noise
- Geoid uncertainty
- Satellite positioning (orbit solution error)
- Environmental corrections

An exact repeat orbit allows processing that decreases two-error sources—geoid error and instrument noise. Without a repeat orbit, it is necessary to use either an independent geoid or sea surface height differences at satellite ground track crossover points. Geoid errors on length scales of 100 km are large (over 20 cm), and dedicated geoid missions (such as GRACE) will not reduce the errors to acceptable levels in the next few decades. Thus, the use of an independent geoid for mesoscale ocean monitoring is not viable.

The remaining option is to use the nonrepeating altimeter data at points where the ground track crosses the ground tracks of prior repeating altimeter satellites. At these points, an accurate estimate of the geoid plus mean sea surface height is possible based on the previous altimeter data (Jacobs and Mitchell, 1997). It is also possible to use the height changes at points where the satellite crosses its own ground track in a short time period. Using the data only at crossovers reduces the amount of data available to a small fraction (about 5 percent) of the total data.

Instrument noise is reduced in an exact repeat orbit. The along-track measurements are spaced about 7 km, which is far less than the length scales of eddies. Filtering, smoothing, or optimal interpolation reduces the measurement noise using several measurements to estimate the sea level. In an exact repeat orbit, the instrument noise is not a significant factor because of this ability to reduce the errors. However, a nonrepeating satellite would have measurements separated by distances much larger than 7 km and would not be able to reduce instrument noise. The measurement points are too widely separated for smoothing. Smoothing to scales on the order of measurement point separation would remove a significant amount of the mesoscale signal. Without smoothing, instrument noise is larger by a factor of 3 to 5. This alone is large enough to preclude the possible use of a nonrepeat orbit.

The inclusion of GPS receivers on satellites has shown that GPS satellite positioning may be accurate enough for real-time applications. The main satellite position errors are long wavelength (40,000 km) with amplitudes less than 10 cm rms and negligible amplitudes at shorter wavelengths. These errors may be

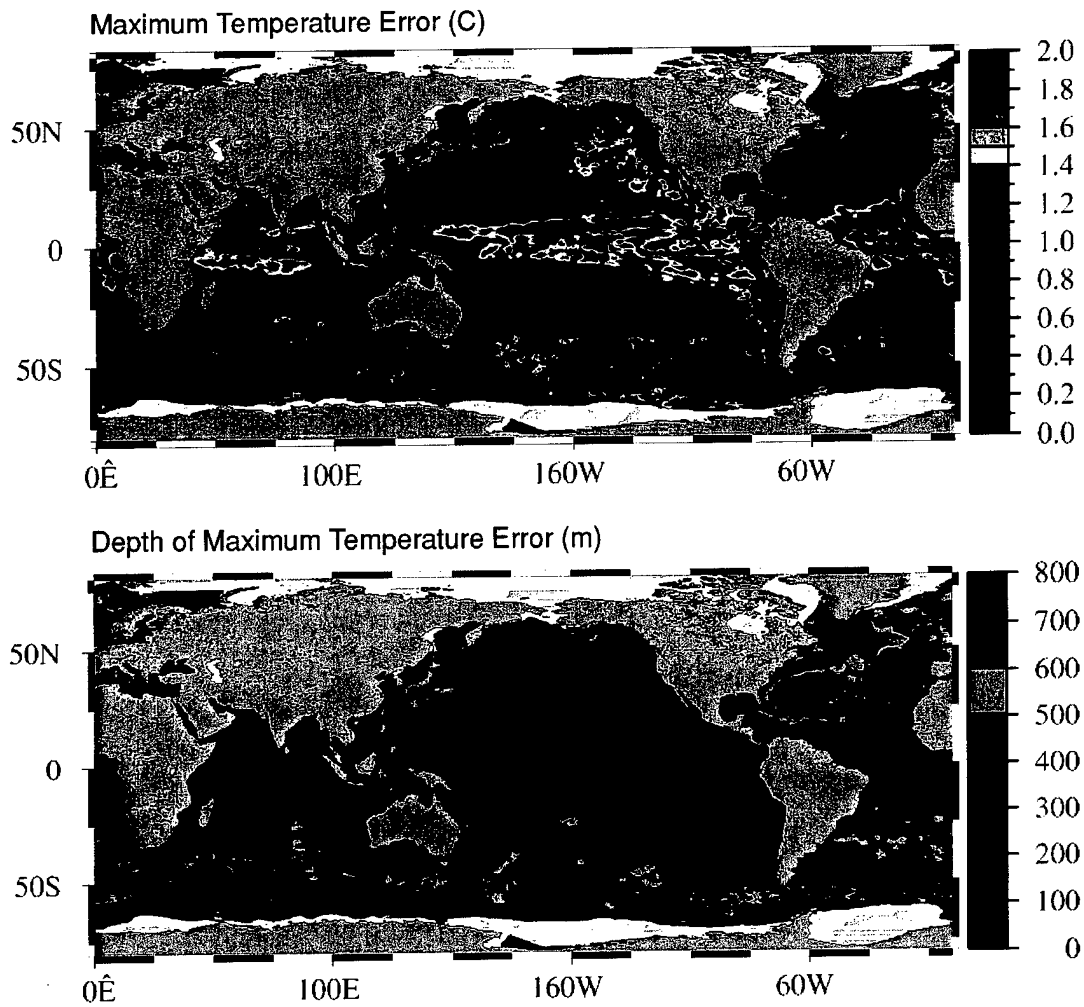

Fig. 7 — Maximum temperature errors due to a 5-cm sea surface height error as computed by MODAS (top) and the depth at which the temperature error occurs (bottom)

removed from the data prior to their use. TOPEX/POSEIDON has demonstrated that real-time orbit solutions are sufficiently accurate for mesoscale observations.

Environmental corrections must include accurate measurements of water vapor content and ionosphere total electronic count. Having the simultaneous measurement of the altimeter radar signal and the water vapor content is necessary due to the short time scales of atmospheric water content variability.

5. RESOLUTION REQUIREMENTS ACCOUTING FOR INTERPOLATION CAPABILITIES

Section 5 indicates that three satellites are required to synoptically observe the mesoscale field (Fig. 6). In addition to providing subsurface environmental structure and forecasts, one purpose of the MODAS and NLOM systems is to provide the capability to interpolate the observed altimeter data. MODAS uses statis-

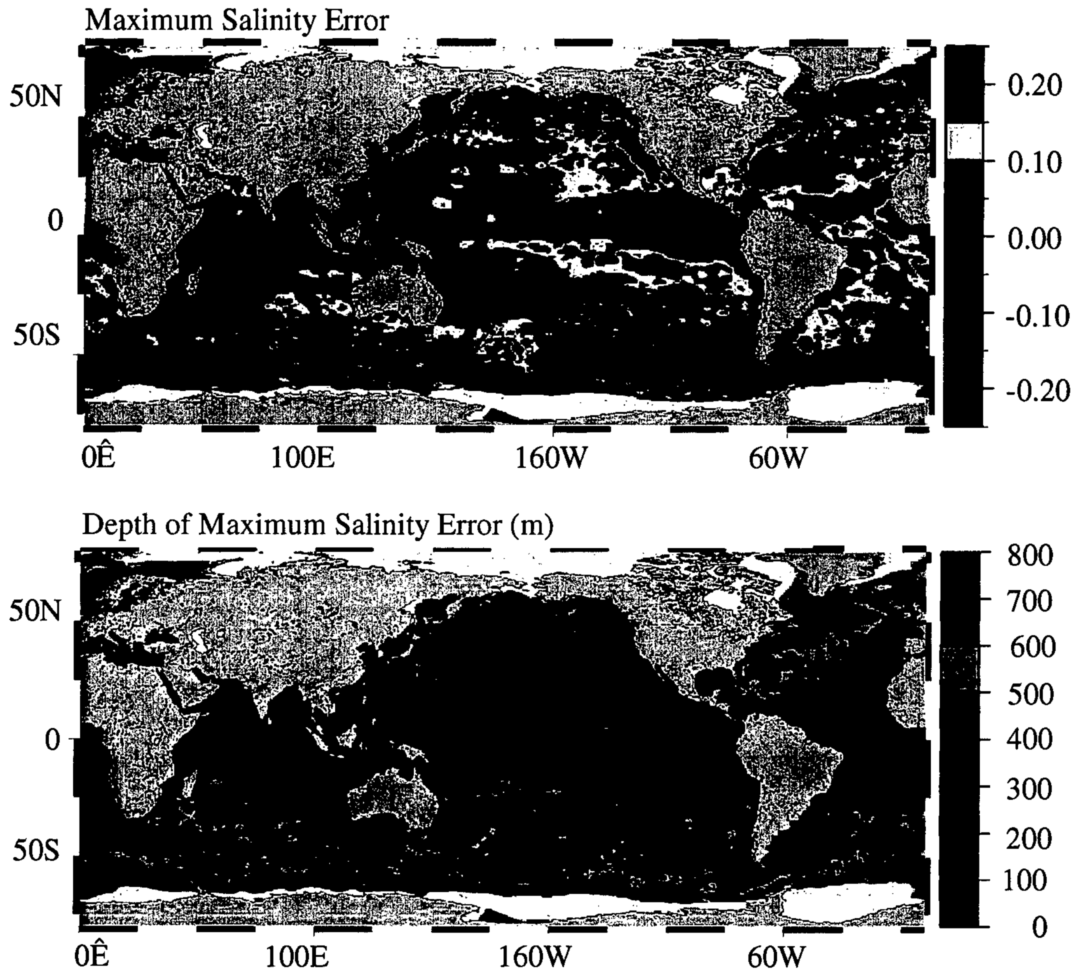

Fig. 8 —Maximum salinity errors due to a 5-cm sea surface height error as computed by MODAS (top) and the depth at which the salinity error occurs (bottom)

tical techniques to accomplish this, and NLOM uses the fundamental dynamical equations. The autocovariance functions in MODAS relate the SSH at one point to all other points in space and time. Thus, given a set of measurements, it is possible to estimate the SSH at unmeasured points through an optimal interpolation. MODAS also provides the expected error in this interpolation technique. Assimilation of altimeter data into NLOM allows the numerical model dynamics to propagate the observed anomalies through space and time. Through these techniques, it is possible to infer, or to a limited extent predict, the unobserved mesoscale field. This then relaxes the requirement to synoptically observe the mesoscale field. We use error estimates from both MODAS and NLOM to determine how different combinations of satellites affect the resulting SSH.

MODAS Expected Errors

Given an observation of an eddy along a satellite ground track, and given knowledge of expected regional eddy behavior such as the propagation speed, MODAS is capable of providing a prediction of the

subsequent eddy development through an optimal interpolation, which also provides an estimate of the expected error (Fig. 9).

The orbit selection has a distinct impact on the expected mesoscale errors. The TOPEX/POSEIDON satellite ground track spacing is relatively coarse. The repeat time for TOPEX/POSEIDON is 10 days, and this is much shorter than the typical mesoscale field time scales (Figs. 5 and 6). Thus TOPEX/POSEIDON oversamples eddies in time, but undersamples them in space. This leads to very low errors along ground tracks and high errors between ground tracks.

The reduced expected errors of ERS-2 are due to the decreased ground track spacing and decreased sampling rate. The expected errors are more uniformly distributed. It is possible to also understand the ability of two or three coordinated satellites. Two ERS satellites are coordinated to reduce the repeat period by half and maintain the spatial resolution. The expected errors (Fig. 9) are reduced from those using only one satellite. The addition of a third satellite slightly reduces errors relative to the two-satellite system.

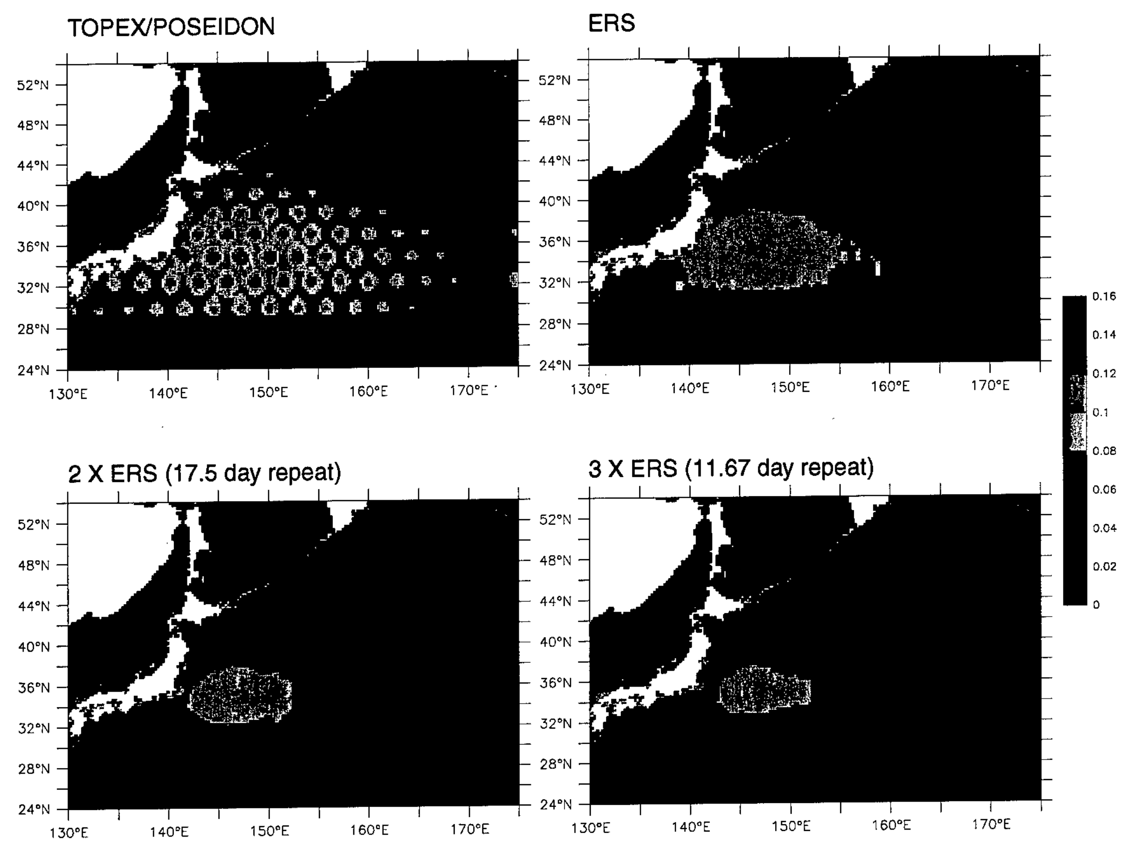

Fig. 9 — Expected Errors from MODAS interpolation of TOPEX/POSEIDON (top left) and ERS (top right) sampling schemes. The TOPEX/POSEIDON sampling is spatially coarse and produces accurate estimates only along the ground tracks. Increasing the number of satellites to two (bottom left) or three (bottom right) decreases expected errors.

NLOM Assimilation Expected Errors

An example of a twin model assimilation indicates the effects of additional satellites on constraining the mesoscale field (Fig. 10). SSH data are measured from NLOM and assimilated into a second NLOM. The model covers the Pacific Ocean north of 20° S at 1/16° resolution. The two models begin with different initial states. Different combinations of altimeter measurements from the first NLOM are assimilated into the second. The measurement ability of a particular arrangement of altimeter satellites is given by the spatial rms difference between the two NLOM models after several months of assimilation. By the end of the experiment, the assimilation model mesoscale state is close to the original. The rms difference characterizes the errors in the ability of the satellite to measure the mesoscale field. The rms difference is measured in the Kuroshio Extension region (30° to 40°N), which is dominated by eddy activity.

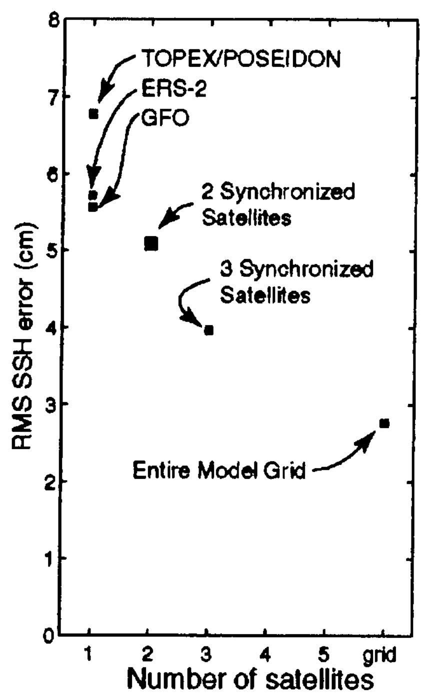

Fig. 10 — The rms difference between the assimilating model SSH and the model from which the data are taken is examined using different satellite systems in the same region as Fig. 9. Orbit selection is important, as demonstrated by the relative error of the single satellite systems. The entire model grid assimilation assimilates data at every grid point instead of sampling only along altimeter tracks. This limit represents the accuracy limit of the assimilation technique. The two satellite system is near the 5-cm error threshold. The three satellite system provides a significant decrease in the error relative to the two satellite system.

Without any assimilation, the rms error is 20 cm. In the limit of perfect knowledge, the entire field at the model grid resolution may be assimilated. This provides an estimate of the model assimilation accuracy limit, which is below 3 cm rms. The assimilation results indicate that one satellite is capable of providing information to substantially reduce the mesoscale error (between 5.5 and 7 cm depending on the satellite). Changing to two satellites indicates a significant drop in the error. Providing three satellites further improves the assimilation accuracy.

Effects of Orbit Selection

Both the MODAS and NLOM results indicate the importance of orbit selection on the error in the mesoscale field. A sampling that is spatially coarse may oversample in time. The result is large errors between ground tracks with small errors along the ground tracks. A more uniform distribution of data allows a more uniform distribution of the expected errors. The similar results of Geosat and ERS orbits in the NLOM assimilation (Fig. 10) and the uniform distribution of the ERS expected errors from MODAS (Fig. 9) indicate that long ERS repeat period is not a problem for mesoscale observation. The requirement on orbit selection should be that the satellite not resample the same point at time scales much shorter than the mesoscale (no less than 20 days, Fig. 5, top).

6. DEVELOPMENT DIRECTIONS

A majority of present operational altimeter data use centers on the mesoscale variability. Research in this area began in the early 1980s, and the systems are becoming operational in the 1990s. This time lag is also appropriate for the use of altimeter data in continental shelf and semienclosed sea regions. Present development for operational systems using altimeter data includes

- **Optimal solution for tides.** The continued inflow of altimeter data is important for this effort. The present 6-year data set available from TOPEX/POSEIDON data is sufficient to begin producing reasonably accurate tide solutions in some continental shelf regions. These solutions surpass the accuracy of prior solutions based on only coastal tide station measurements (Fig. 11). To reduce errors significantly, the altimeter time series needs to be extended by a factor of 4. The extended time period will also allow resolution (separation) of major tidal constituents with similar frequencies. Alternatively, data along new ground tracks would provide valuable information. The need for continued improvement of tidal solutions requires the continuing collection of altimeter data. Using a single satellite, the repeat period must be chosen so that the tidal constituents will not be aliased to frequencies at which significant ocean variability occurs. These frequencies are the mean, annual, and semiannual frequencies. In a sun synchronous orbit, the solar tides are aliased to the mean and annual frequencies.

- **Regional model evaluation.** Data are required to evaluate the accuracy of regional ocean models before operational transition. The altimeter data have been used to evaluate the model storm surge and other responses to wind forcing (Fig. 12). Altimeter data have proven to be one of the most useful data sets because of the length of the time series. In addition, although the spatial density of the ground tracks is relatively low on continental shelf scales, the altimeter spatial density is still greater than that provided by in-situ mooring deployments. Thus, the altimeter data provide an evaluation tool better than other available measurement methods.

- **Regional boundary conditions.** Regional ocean models suffer greatly from lack of data to specify boundary conditions. The mesoscale circulation in the deep ocean has a large impact on the coastal environment. A regional model must contain synoptic boundary conditions. There are two methods for obtaining the boundary conditions. The first is to directly use the altimeter data at the model boundary by providing SSH along with temperature and salinity from MODAS. A second method is to couple the regional model to a large-scale basin or global model that is assimilating altimeter data and contains the mesoscale circulation. In either case, altimeter data improve the boundary conditions available for use in initializing regional models.

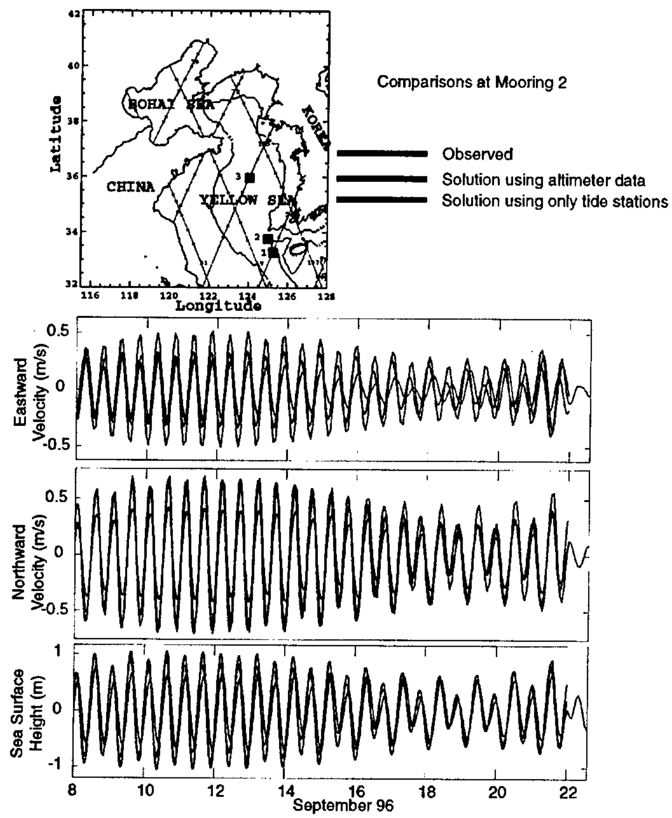

Fig. 11 — An inverse solution to the tides is made using altimeter data in one case and coastal tide stations in a second case. Comparison of tidal solutions to in-situ current measurements indicates that the solution based on altimeter data is more accurate than the solution based only on tidal stations.

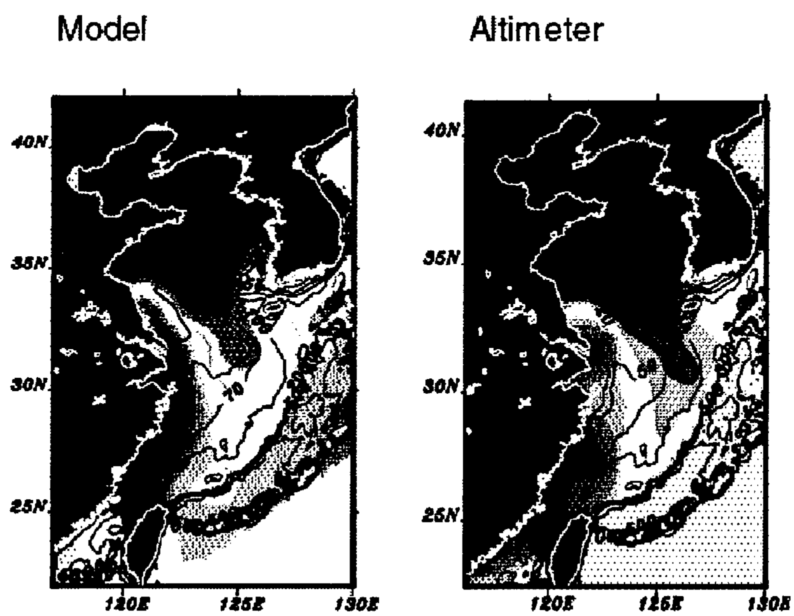

Fig. 12 — Numerical model transition to operational use requires extensive validation against observational data. SSH response to a northerly wind burst in the Yellow and East China Seas from a numerical model (left) is compared to identical analysis of the TOPEX/POSEIDON altimeter data (right).

7. ADDITIONAL CONSIDERATIONS

Several additional points must be considered in the requirements for altimeter data.

Present and Future Capabilities

Presently there are two altimeter satellites returning data in real time. The data from the TOPEX instrument are delivered to the Naval Oceanographic Office within 24 hours of measurement, and the data from the ERS-2 satellite are delivered within 48 hours. The requirement for three altimeter satellites does not imply that there is no benefit before this threshold is met. The three-altimeter requirement would provide the ability to synoptically observe the mesoscale circulation. One satellite provides useful information over a majority of the open ocean areas if the data are used in conjunction with the MODAS or NLOM systems. The benefit of a single satellite depends on the sampling characteristics. This is apparent in the results from MODAS (Fig. 9) and NLOM (Fig. 10). In addition, from the MODAS and NLOM results, expected errors decrease with additional satellites. With two satellites, the expected errors in NLOM are reduced to 5 cm rms, and the MODAS expected errors decrease as well.

Measurements along a New Orbit or Ground Track

Launching into a new repeat orbit may be done under certain circumstances. For a program planning to launch a single altimeter satellite with no planned follow-on satellite, it would be desirable to maximize the data benefits. Thus a program of one satellite should overfly an existing ground track. However, a long time period project planning to fly several altimeter satellites in succession may benefit by changing to a new ground track to maximize the coverage of ocean processes.

The drawback to flying over a new ground track is that it will take time to build a new mean sea surface and corresponding statistics, and the time required depends on the repeat period. Given no other information, the error in the mean is the rms variability divided by the square root of the number of samples. However, if there is an overlap with a repeat altimeter with a known mean, the rms variability may be substantially decreased. For example, a mean has been formed along the ERS-1/2 ground tracks (which has a 35-day repeat period) with only 2-years' data through a combination with TOPEX/POSEIDON. First, the TOPEX/POSEIDON-measured SSH anomaly is removed from the ERS-1/2 data. This substantially decreases the variability in the data. The ERS-1/2 mean is then formed, and the error in the mean is significantly reduced. For a 31-day repeat orbit that has a temporal overlap with other altimeters, one year of data would be sufficient to form a mean SSH with acceptable error characteristics over a majority of the globe.

8. FINAL RECOMMENDATIONS

These requirements and recommendations are based on the results of the MODAS and NLOM expected errors. The timeliness, resolution, and temporal sampling scales derived here may also be found in the Military Requirements for Defense Environmental Satellites (MJCS 154-86, revalidated 18 Nov., 1993 by USCINCLANT and USCINCPAC, CNOC 3140 ser 5/400).

Accuracy and Timeliness Requirements

A satellite system with the measurement accuracy and timeliness of the present TOPEX/POSEIDON satellite would satisfy operational requirements. The accuracy and timeliness requirements include the following:

- **Timeliness.** SSH, atmospheric correction parameters, and orbit solutions are required within 48 hours. Wave heights are required within 3 hours. The major ocean fronts and eddies of the western boundary currents can shift significantly in 5 days. To avoid significant degradation in the eddy field, the altimeter data (and the necessary correction fields and orbit solutions) needs to be under 48 hours old.

- **White noise level below 3 cm rms.** In an exact repeat orbit, the white noise level of present altimeter satellites is sufficient for present Navy applications. Since the eddy mesoscale field has scales greater than the 7 km along track sampling rate, proper interpolation or model assimilation reduces errors due to white noise to 1 cm or less. Prior studies of the overall errors indicate that the remaining correlated errors are within acceptable levels.

- **Total range error under 5 cm (peak error).** This requirement is derived based on the errors induced in the subsurface temperature and salinity by errors in dynamic height measurements. A 5-cm dynamic height error propagates through operational systems to peak 1° to 2°C temperature errors. This requirement is for altimeter data processed to the one sample per second rate.

- **Real-time orbit solutions.** Near real-time orbit solutions are expected to contain undesirable errors at the one cycle per satellite orbit revolution (1 cpr) frequency. In order to reduce orbit solution errors to an acceptable level, some postprocessing must be done by removing a 1 cpr signal from the data. Once required to remove a 1 cpr orbit error, the orbit error amplitude at this frequency is relatively inconsequential. However, it is important that errors at higher frequencies be sufficiently small that the dynamic height derived from the altimeter data is not corrupted. Thus, we require under 1-m error at 1 cpr and less than 2-cm integrated errors at higher frequencies.

Resolution and Sampling Requirements

- **Exact repeat orbit.** While data may be obtained from an altimeter that is not in an exact repeat orbit, the quality and quantity of useful data are significantly diminished. The loss of data in a nonexact repeat orbit is so great that an exact repeat orbit must be a requirement. An exact repeat orbit requires that the satellite be held to within a 1-km-wide swath of a predefined ground track.

- **Time and space resolution.**

  One instrument: Given only one altimeter sensor, the data must be used in conjunction with the MODAS and/or NLOM systems. A single satellite is not capable of synoptically observing the ocean mesoscale. For a single altimeter, the repeat orbit period should be greater than the typical mesoscale time period of 20 days.

  Two instruments: At least two altimeter sensors are recommended for NPOESS. Errors in operational MODAS and NLOM products are reduced. In addition, because the altimeter is not a mission critical sensor for NPOESS, the loss of the altimeter sensor on one platform will still allow MODAS and NLOM products to be generated by using data from the second altimeter sensor. With only one altimeter sensor on NPOESS, failure of the instrument would result in a substantial period during which the Navy would not receive MODAS or NLOM products. For two altimeters, the time period between sampling the same point on the ground should be greater than the typical mesoscale time period of 20 days.

- **Tidal aliasing.** Major tidal constituents should not be aliased to frequencies that contain significant ocean variability. These frequencies include the annual, semiannual, and mean.

ACKNOWLEDGMENTS

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